Modern Tools and Techniques for Designing Advanced Accelerators

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26 April 2017
Brookhaven National Laboratory

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~~Modern~~ Tools and Techniques *That Work* for Designing Advanced Accelerators

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Introduction

- Important aspects of effective design and modeling tools
  - Physics
  - Integration and workflow
  - Throughput (e.g., efficiency, parallelism)
  - Continuous improvement
- We'll illustrate some of these factors in APS-U modeling
  - For details, see references at end of presentation
  - Also see talks by G. Decker and Y.-P. Sun
- Simulations described are routinely performed for APS-U
  - Results shown for latest 41-pm reverse-bend lattice, unless otherwise noted

Integration and Workflow

- Good workflow is essential to productivity, sophisticated simulation
- Signs of poor workflow
  - Frequent manual transfer or translation of data between programs.
  - Fragile interfaces between tools.
  - Almost as much effort to repeat a calculation as to do it the first time.
  - Little use of parallelism.
- To improve matters
  - Use self-describing files (e.g., SDDS), especially in changing environment.
  - Avoid making GUIs: development is relatively resource intensive
  - Instead, use scripting to facilitate automation and increase throughput
  - Buy a cluster: computers are cheap compared to people.

Key APS Software Used for APS-U Sims.

- `elegant/Pelegant`: accelerator design; single-particle and collective beam dynamics; MPI-based parallelism
- SDDS library: (parallel) file I/O using self-describing data
- SDDS toolkit: generic, scriptable data processing/display
- `geneticOptimizer`: generic cluster-based MOGA optimization
- `ibsEmittance`: intrabeam scattering
- `touschekLifetime`, etc.: lifetime calculations
- `sddsbrightness`, `sddsfluxcurve`, etc.: x-ray calculations
- `clinchor`: point-particle multibunch instabilities with arbitrary fill patterns
- Open source, multi-platform

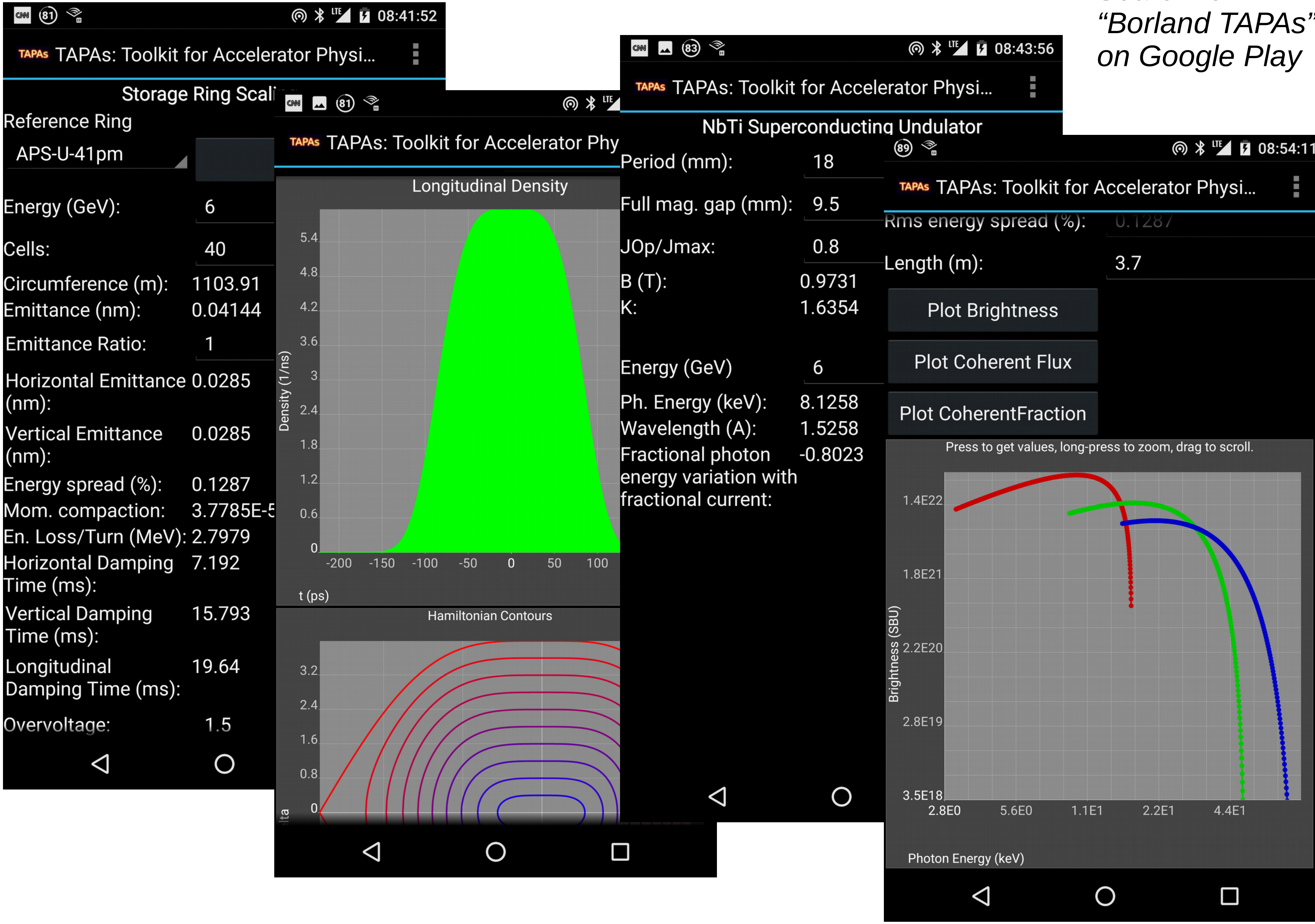
Other Key Software Used for APS-U Sims.

1: W. Bruns, Linac 2002, 418.
2: I. A. Zagorodnov et al. PRSTAB 8, 042001.
3: T. Weiland, NIM 216, 329 (1983).
4: M. Ady et al, IPAC14, WEPME038.
5: R. Kersevan et al., PAC93, 3848.
6: operafea.com
7: M. Borland, PAC2013, 1364.

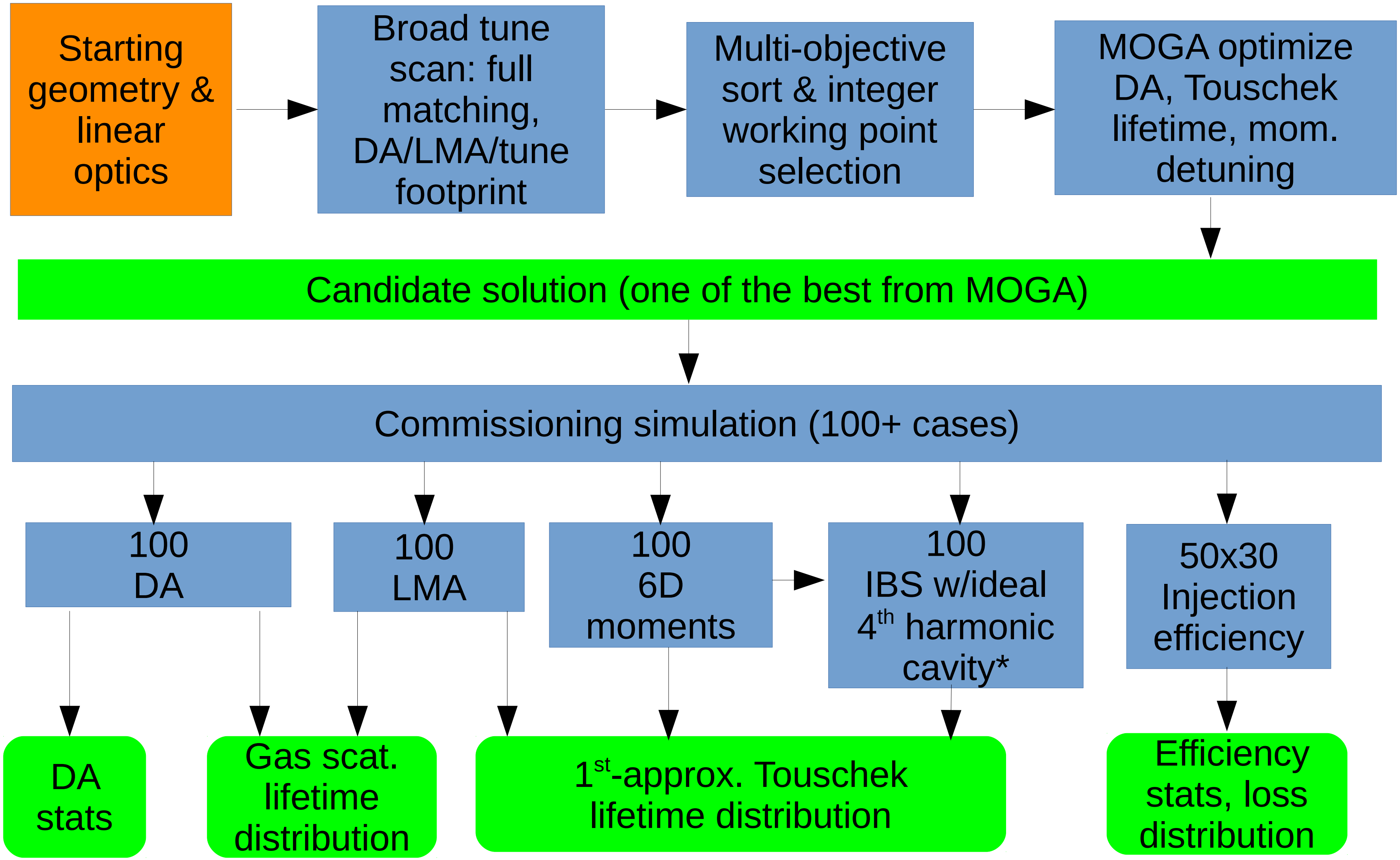
- Wakes:
  - GdfidL [1]
  - ECHO [2]
- HOMs: URMEL [3]
- Vacuum modeling:
  - SYNRAD+ [4]
  - MOLFLOW+ [5]
- Magnet design: OPERA [6]
- Open-source scripting languages, e.g., bash, csh, tcl
- “Back of the envelope” calculations: TAPAs [7]

TAPAs Android App

Search for “Borland TAPAs” on Google Play

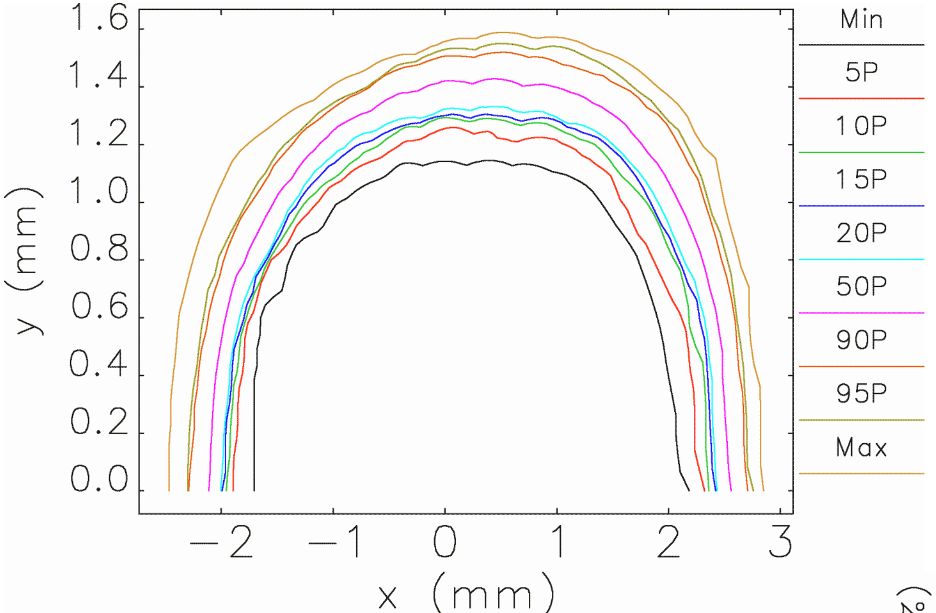


APS-U Optimization and Evaluation



*hereafter "4HC"

Ensemble evaluation

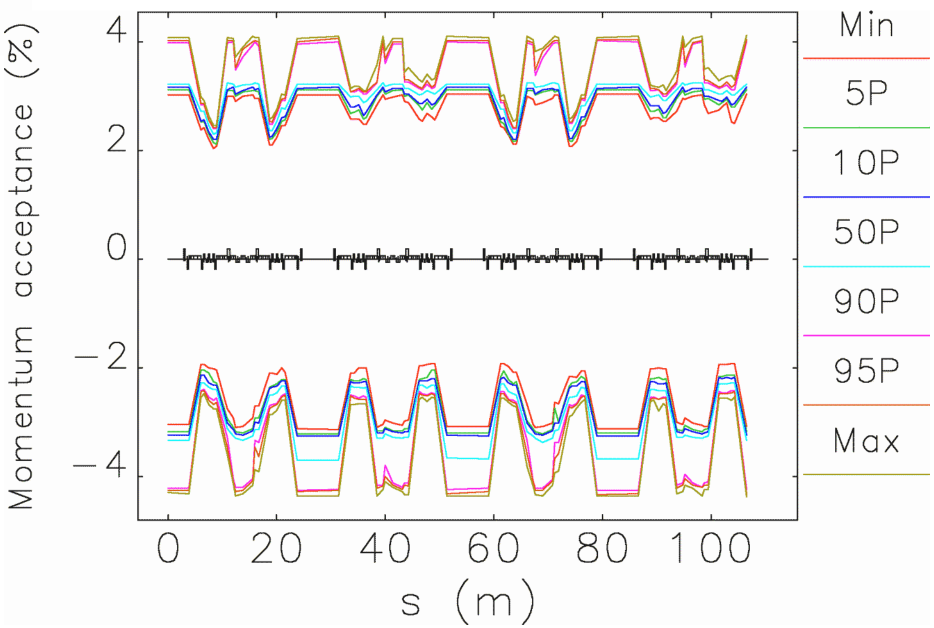


Percentile contours of DA over 100 ensembles.

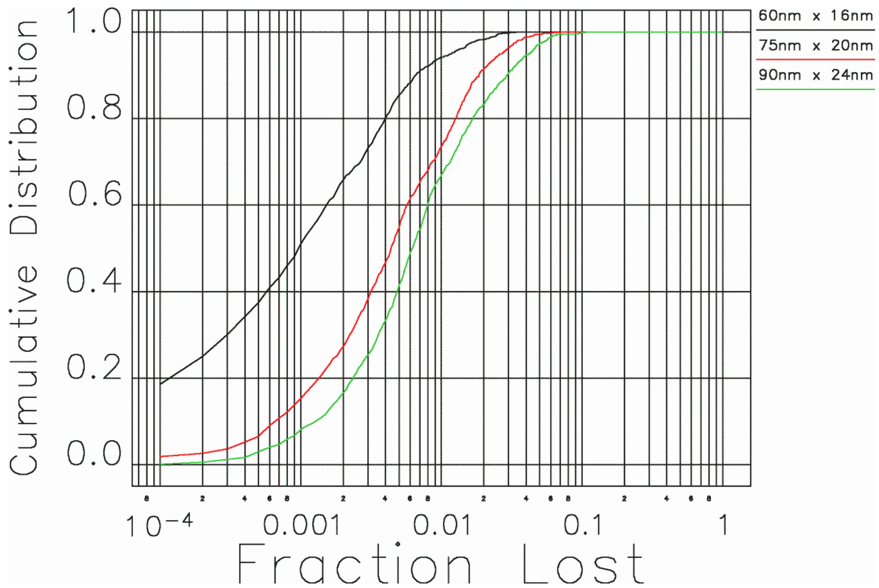
DA suitable for on-axis swap-out injection.

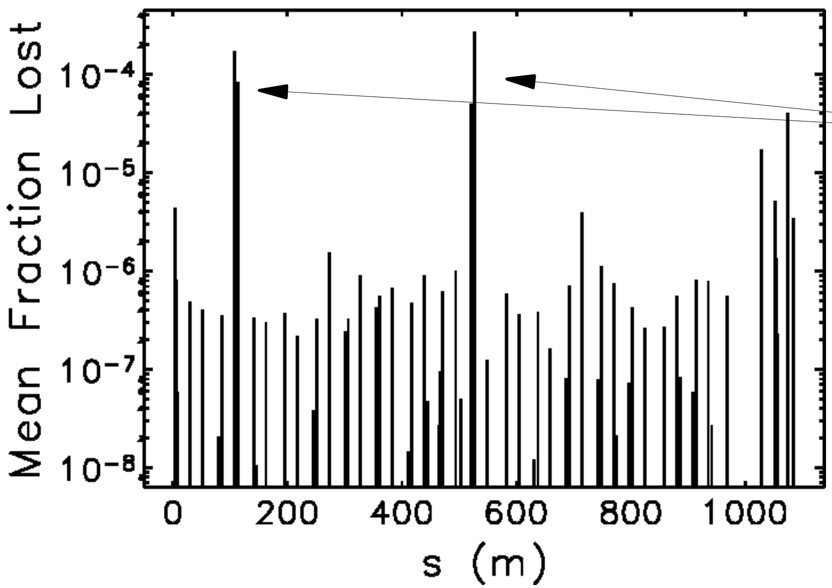
Percentile contours of LMA over 100 ensembles

Individual LMA results will be used to compute Touschek lifetime distribution.



Injection efficiency



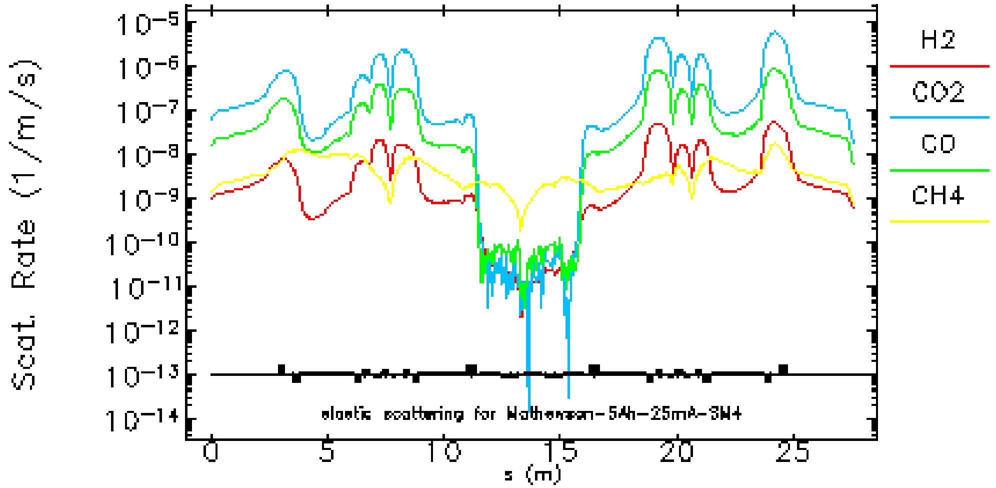


- Injection efficiency modeled using ±4σ uniform distributions with gaussian weighting, for high accuracy when losses are small
- 30 shots simulated for each of 50 ensembles, including jitter, mismatch, etc.
- Find that a 50% increase in booster emittances does not result in excessive losses
- Losses largely at small ID apertures (e.g., helical SCU with r=3mm)
  - Collimation scheme needs further work

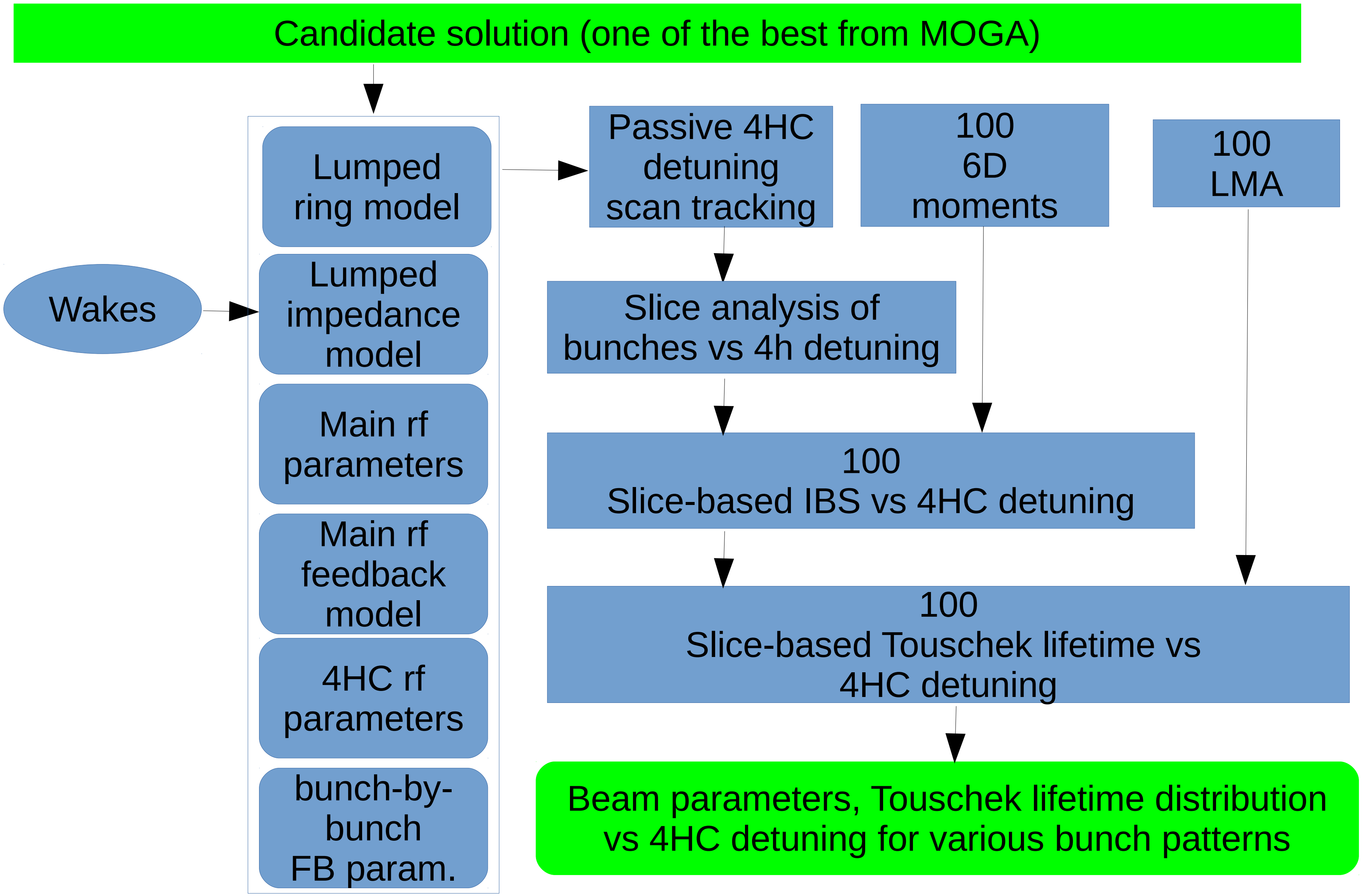
Gas scattering lifetime

- Computed species-specific pressure profiles using SYNRAD+ and MOLFLOW+
  - Calculations give pressure profiles after 5, 100, and 1000 Ah of operation
- Combine with 100 ensemble evaluation results
  - DAs give betatron acceptance for 100 elastic scattering results (script: `elasticScatteringLifetimeDetailed`)
  - LMAs give momentum acceptance for 100 bremsstrahlung scattering results (script: `bremsstrahlungScatteringLifetimeDetailed`)
- Calculation gives local, species-specific out-scattering rates
  - Integration gives total scattering rate, lifetime
  - Gives guidance to vacuum engineers on where to concentrate effort

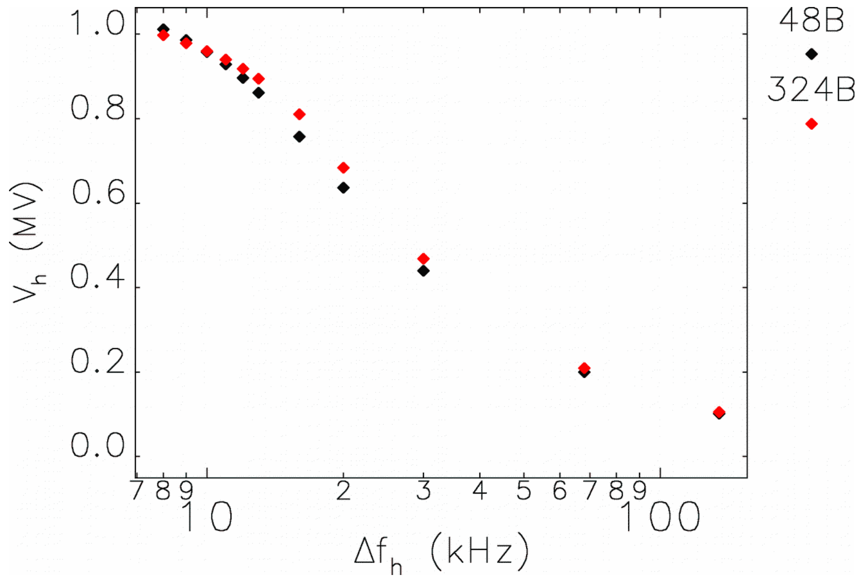
Elastic gas scattering rates for 41pm lattice after 5 A*h conditioning, at 25 mA



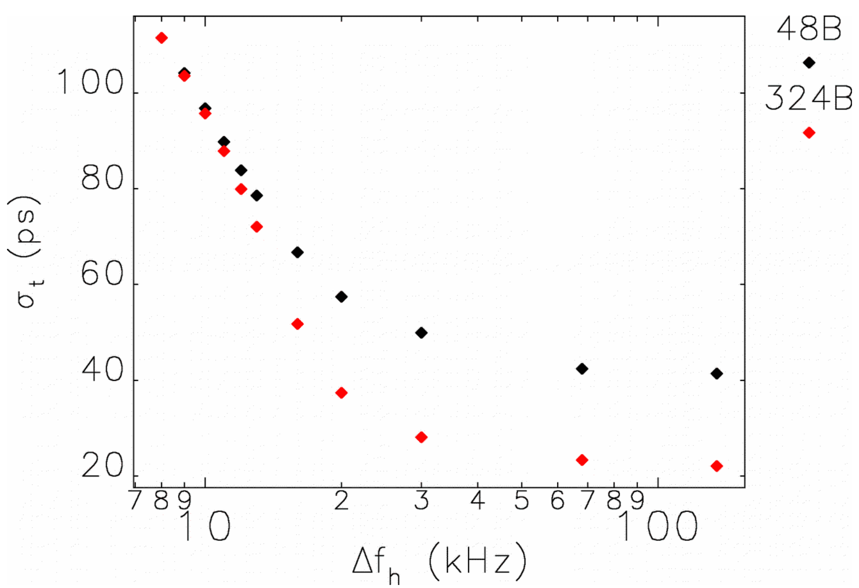
MWI, IBS, Touschek Lifetime

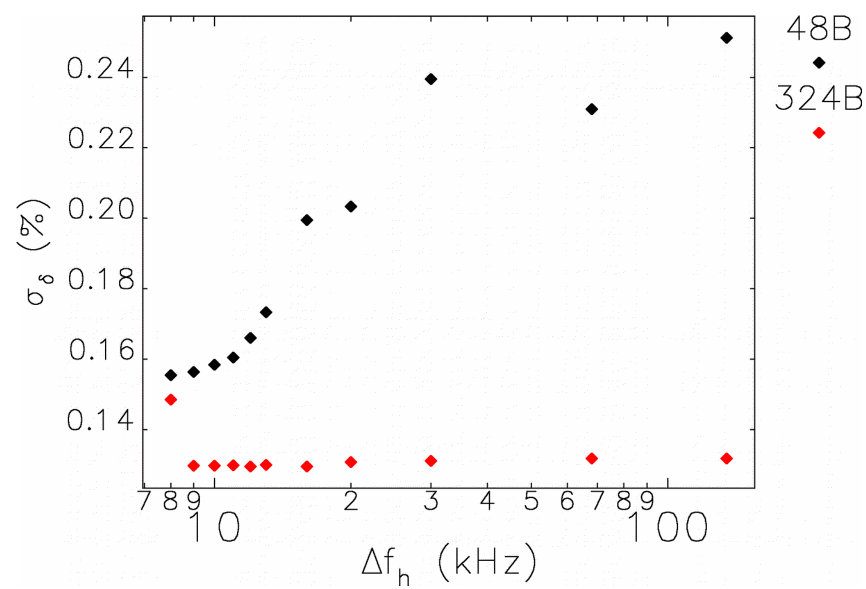


Bunch lengthening for two fill patterns

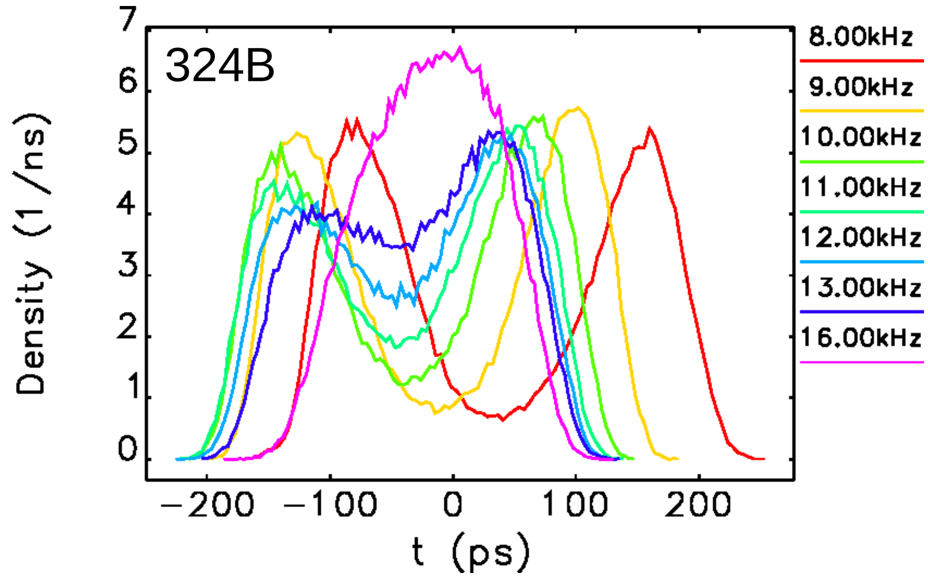


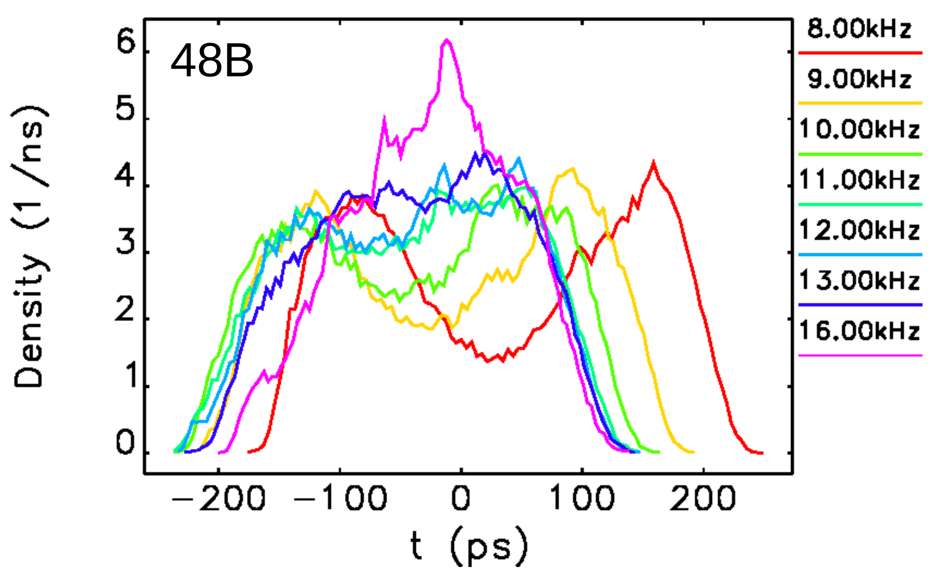
- Voltage in 4HC is computed self-consistently, including short-range impedance
- Microwave instability inflates energy spread and bunch length for 48-bunch fill
- Stretching the bunch with the 4HC partly suppresses instability





Bunch shapes vs 4HC detuning

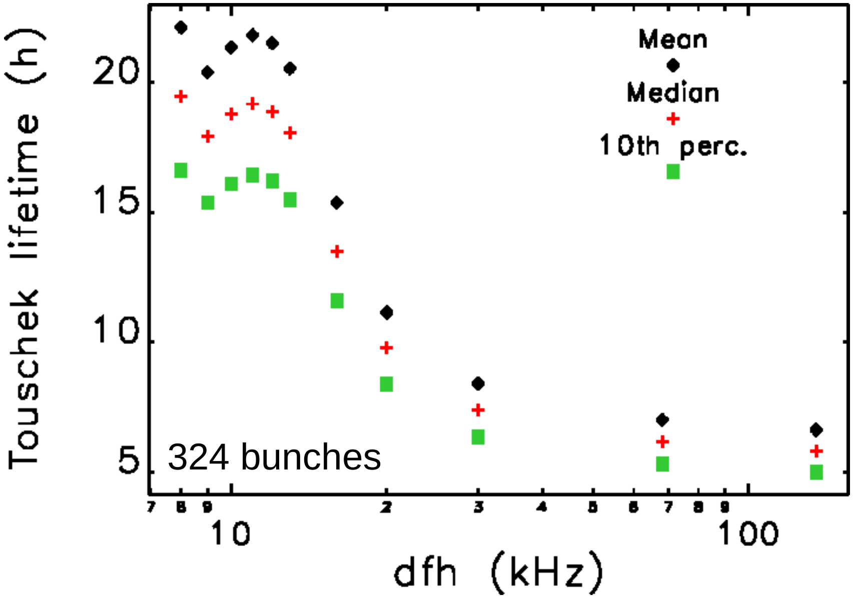


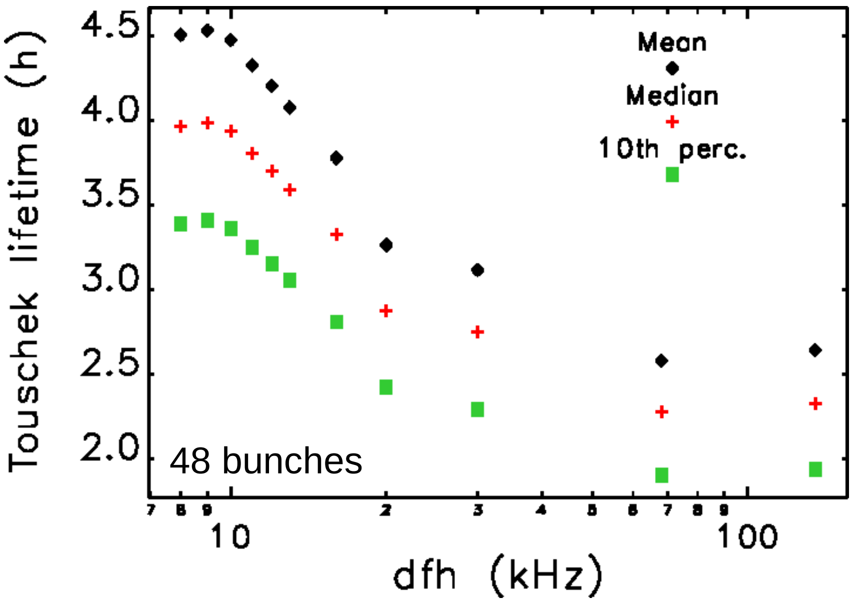


- As bunch is stretched, it eventually starts to split in two
- Maximum Touschek lifetime may not correspond to maximum rms bunch duration
- Use simulated longitudinal distributions to compute IBS, Touschek lifetime

Touschek lifetime at 200 mA

- Touschek lifetime calculation uses
  - Longitudinal density from tracking with harmonic cavity, impedance
  - IBS-inflated emittance, energy spread from slice-based calculation
  - LMA data from ensemble tracking
- Partially splitting the bunch can increase lifetime, up to a point
- Additional Touschek lifetime studies include literal simulation of Touschek scattering (see A. Xiao pubs in refs.)





Performance for several modes

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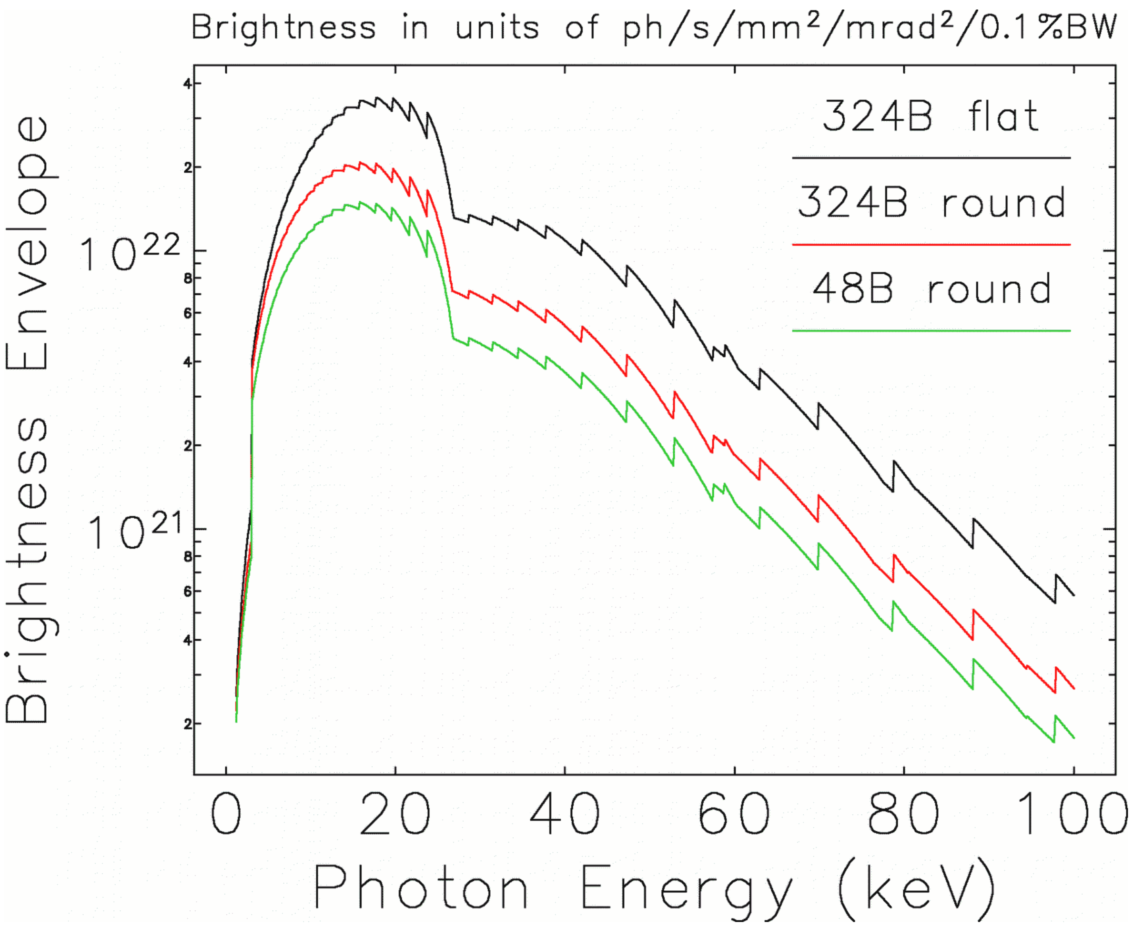
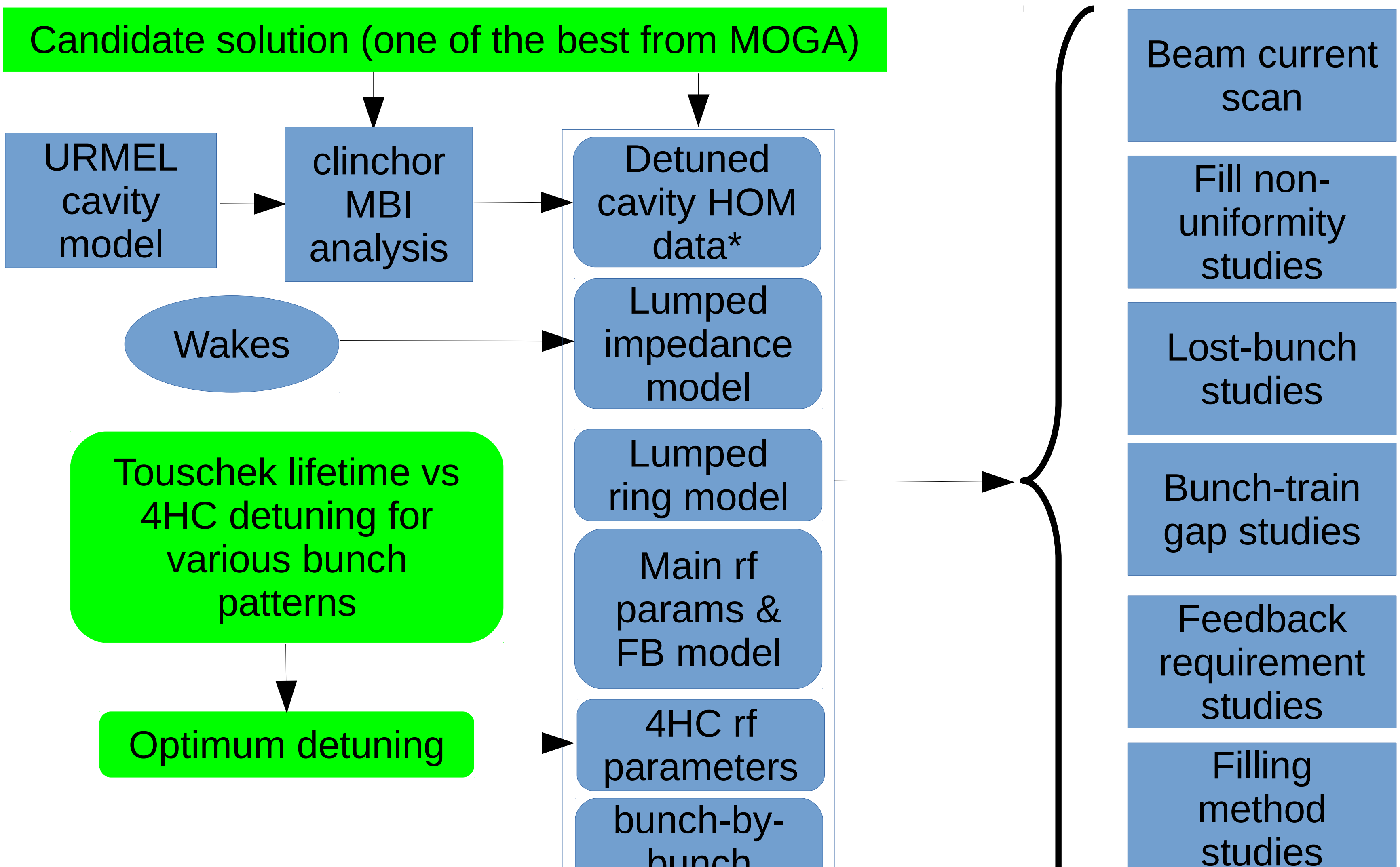


Results for previous 41-pm lattice [2].

- Data from `elegant` and `ibsEmittance` used with `sddsbrightness` to evaluate brightness.
- Includes energy spread increase due to microwave instability from tracking with the impedance model and 4HC tuned to maximize lifetime
- Curves are envelopes over possible 3.7-m-long SCUs [1] with front-end limits included.

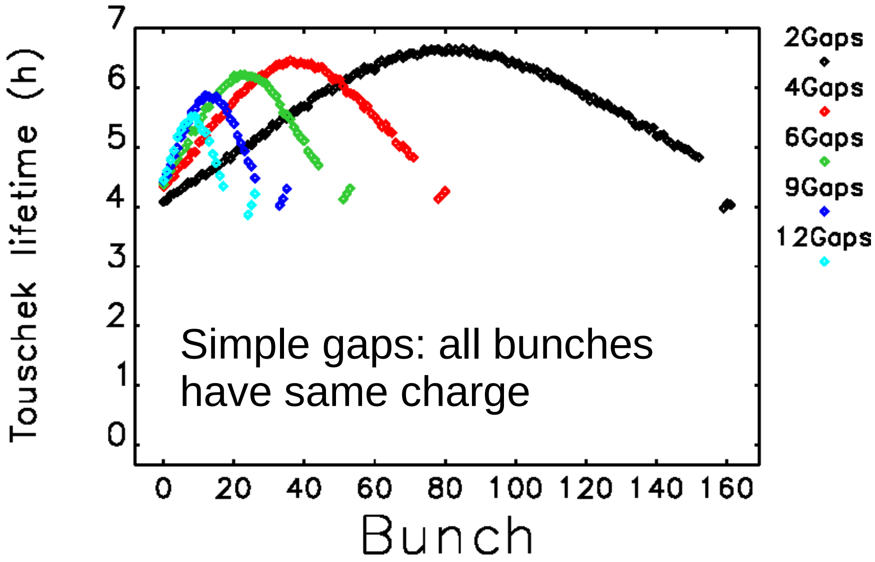
1: S.H. Kim, NIM A 546, p. 604 (2005).
2: M. Borland et al., NAPAC16, WEPOB01.

Multi-bunch, multi-particle collective effects

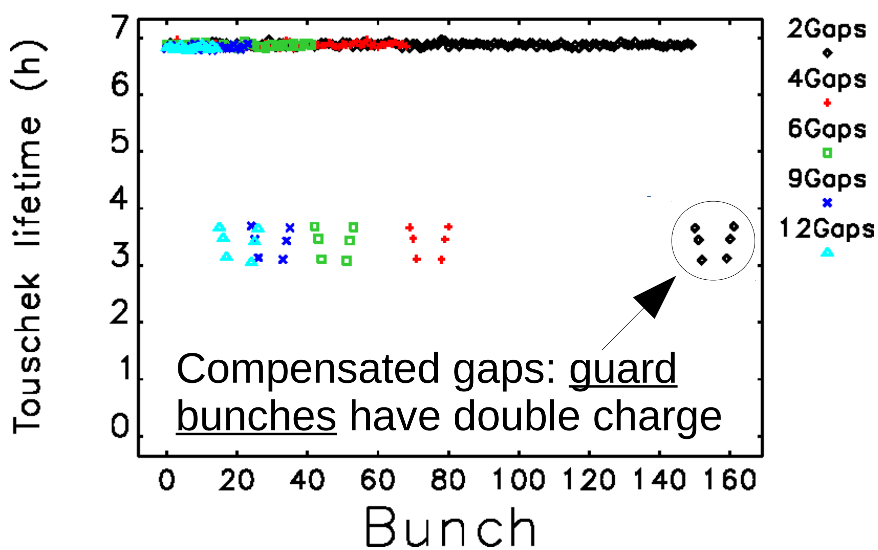


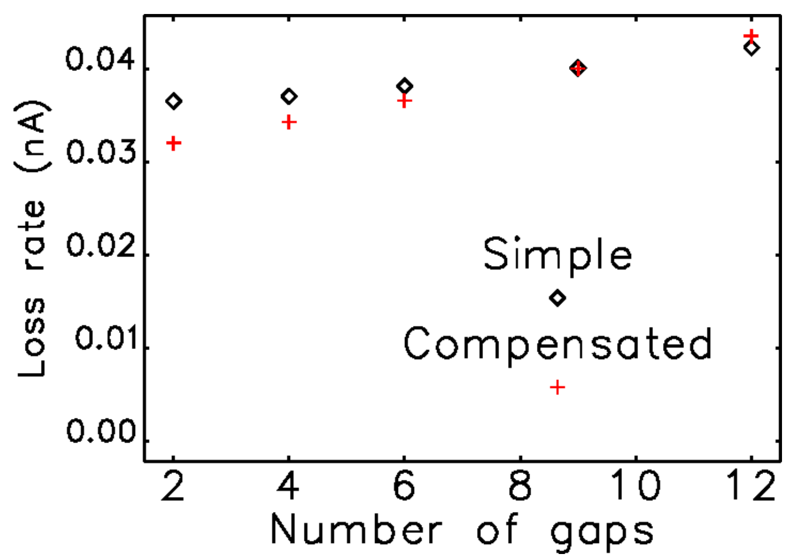
*simulations usually performed w/ and w/o HOMs

Bunch train gaps and Touschek lifetime

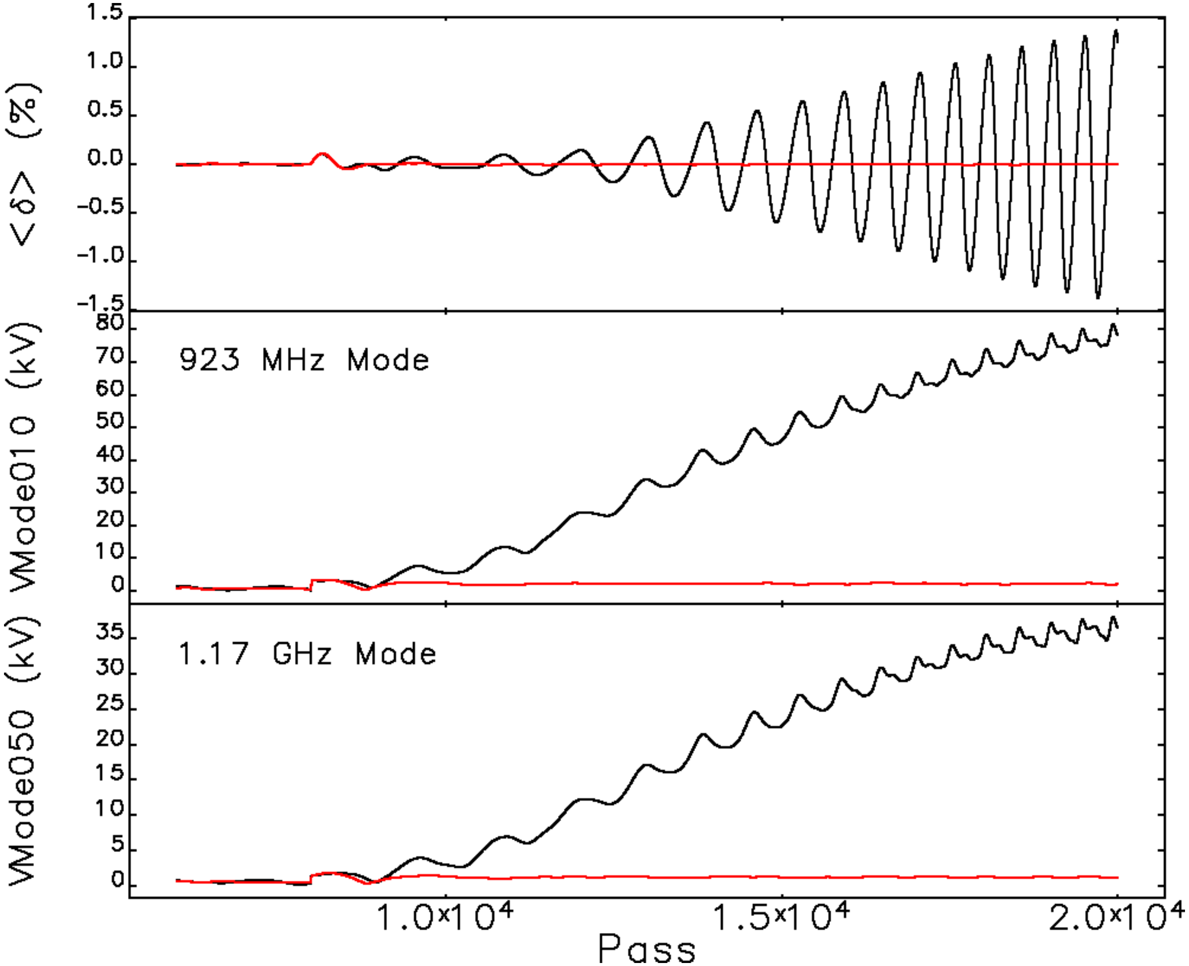


- In 324-bunch round-beam mode, need gaps to fight ion instabilities
- Introduces transients in rf cavities, in spite of feedback
- Modulates bunch distribution, Touschek lifetime
- Using “compensated” gaps is found to help, within limits





Impact of a lost bunch (failed swap-out)



Black: 1.8 kV LFB cap
Red: 6 kV LFB cap
Results for 67-pm lattice

- Swap-out uses very fast kickers to extract one bunch and inject a replacement
- What if replacement fails to arrive?
- Simulated using a kicker to kill one bunch of 48 after equilibriation
- Without adequate longitudinal feedback strength, beam is lost
- Suspect involvement of two monopole HOMs
- Can evaluate HOM detuning strategies, estimate required LFB strength

Single-bunch collective effects

Commissioning simulations (100+)

Wakes

Distributed impedance model

Element-by-element ring model

Idealized main rf parameters

Idealized 4HC parameters

Single-bunch instability thresholds

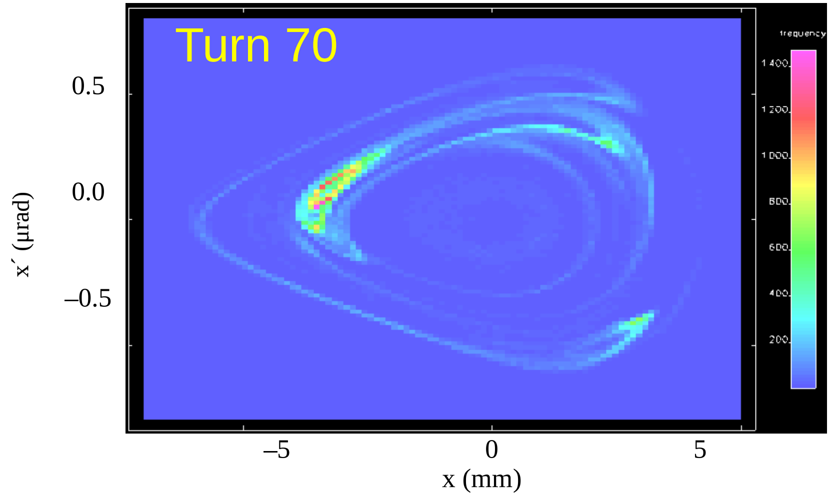
Single-bunch injection studies with errors

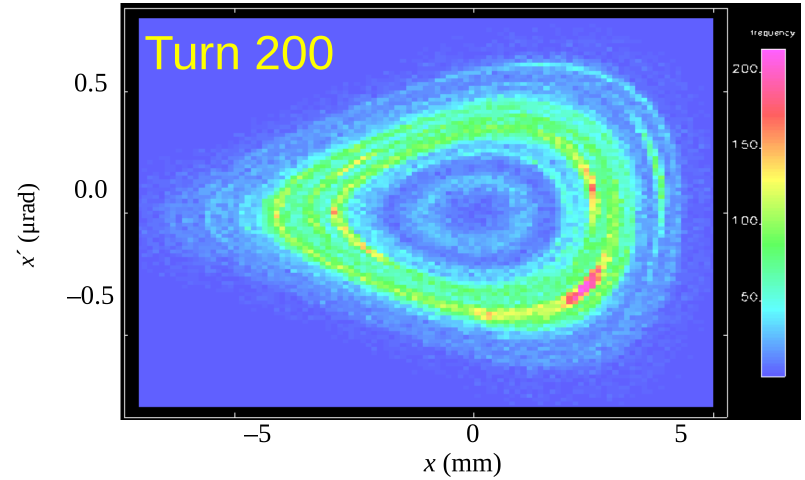
Use of a distributed impedance model and element-by-element tracking reveals details not seen in simpler models.

Computing requirements considerably increased.

Collective effects make accumulation very challenging for the 90-pm lattice

- In 324 bunch mode with 0.63 mA/bunch, accumulation works as hoped
- At higher currents collective effects can lead to particle loss during accumulation





- Bunch-by-bunch feedback has limited utility
  – Narrow margin for tuning to avoid beam loss
  – Significant strength required
- One of the reasons we abandoned accumulation
- Phenomenon observed in APS today, validates simulations [S. Shin et al.]

Conclusion

- Simulations performed for APS-U use tools developed at APS and elsewhere
  - Fairly well integrated, scriptable, parallelized
  - High throughput and sophistication
- Modeling efforts to continue through design, construction, commissioning
  - Increased detail, fidelity, and sophistication
  - Continued benchmarking
- On-going and planned developments include
  - GPU version of `elegant` (now in alpha release)
  - Ion simulation in `elegant` (under test)
  - Tools for easier preparation of impedance
  - Continued expansion of examples library

Additional references

- APS tools
  - clinchor: L. Emery, PAC 93, 3360.
  - elegant: M. Borland, APS LS-287, Sept. 2000.
  - gpu-elegant: J. R. King et al., IPAC15, 623. (Result of Tech-X SBIR project.)
  - ibsEmittance: M. Borland et al., PAC03, 3461; A. Xiao et al., IPAC15, 559.
  - Pelegant: Y. Wang et al., AIP Conf. Proc. 877, 241 (2006).
  - SDDS I/O: H. Shang et al., IPAC09, 347.
  - SDDS Toolkit: M. Borland, PAC95, 2184; R. Soliday, PAC03, 3473; M. Borland et al., PAC03, 3461
  - touschekLifetime: A. Xiao et al., PAC07, 3453; A. Xiao et al., IPAC15, 559.
  - Software: http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/software.shtml
  - Documentation: http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/oagSoftware.shtml
- APS-U accelerator simulations
  - Optimization: M. Borland et al., IPAC15, 1776; M. Borland et al., NAPAC16, WEPOB01; Y. Sun et al., NAPAC16, WEPOB14; Y. P. Sun et al., NAPAC16, WEPOB14.
  - 90-pm “accumulation” lattice: Y. Sun et al., IPAC15, 1803.
  - Commissioning: V. Sajaev et al., IPAC15, 553.
  - Ensemble evaluation: M. Borland et el., IPAC15, 1776; M. Borland et al., NAPAC16, WEPOB01
  - Beam loss, collimation: A. Xiao et al., NAPAC16, WEPOB22.
  - Gas-scattering lifetime: M. Borland et al., IPAC15, MOPMA008, B. Stillwell et al., IPAC15, MOPWI012.
  - Touschek lifetime: A. Xiao et al., IPAC15, 559.
  - Fringe-field modeling: M. Borland et al., NAPAC16, THPOA13.
  - Rf feedback modeling: T. Berenc et al., IPAC15, 540.
  - Impedance and single-bunch collective effects: R. Lindberg et al., IPAC15, 1822; R. Lindberg et al., IPAC15, 1825; R. Lindberg et al., NAPAC16, WEPOB08.
  - Multi-bunch collective effects: M. Borland et al., ICAP15, 61; L. Emery et al., IPAC15, 1784; M. Borland et al., IPAC15, 543;
  - Ion effects: J. Calvey et al., NAPAC16, THPOA14.
  - Injector modeling: J. Calvey et al., NAPAC16, WEA1CO03.

Key features of elegant

- Code structure makes it easy to enhance
- Automated regression testing reduces introduced bugs
- SDDS input/output provides robust interfaces
- Serial and MPI-based parallel versions
- Waveform-driven kickers, modulation, ramping
- Modification of beam with external programs
- Optimization of calculated quantities and tracking results
- Symplectic tracking, optional synchrotron radiation
- DA, LMA, FMA
- Fast tracking with amplitude and momentum detuning
- Single-bunch wakes/impedances
- Cavity modes and long-range wakes
- Beam-loaded cavities with feedback
- Bunch-by-bunch feedback

Facilitates continuous improvement